STANDARD OPERATING PROCEDURE

FOR

RADIANCE RESEARCH M903 INTEGRATING NEPHELOMETER

STI-999213

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PREFACE

This SOP follows the outline for CRPAQS SOPs with the result that some of the information you may need first is buried. For the page numbers of the following sections, see the Table of Contents on the next page.

Section number, heading, and brief description

11.1 Quick Start Instructions. Brief instructions adequate to begin collecting data with the nephelometer. These steps are the minimum required to begin collecting data.

11.2 Checklist for Initial Operation. A checklist to be used after a nephelometer has been installed in a CRPAQS shelter at the site to be sure it is collecting data according to the recommendations of this SOP.

9.1 Nephelometer Settings. A listing of the screens available on the LCD display on the nephelometer and a partial description of their use and interpretation (see also Section 5.3 of the Radiance Research manual).

10.2 Rapid Field Calibration. The procedure for calibrating the nephelometer zero and span and recording the data by hand from the **Main Screen** of the nephelometer.

10.3 Extended Calibration. The calibration procedure which records 5-min average zero and span data in the nephelometer memory.

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RADIANCE RESEARCH M903 INTEGRATING NEPHELOMETER

1. SCOPE AND APPLICABILITY

1.1 Integrating Nephelometer Measurement of Light Scattering

The Radiance Research Model 903 Nephelometer measures light scattering in an airflow that passes through the scattering chamber of the instrument. The measurement geometry has been designed so that the instrument reading is almost proportional to the light-scattering coefficient, which indicates the total amount of light scattered into all directions by the air sample in the scattering chamber. (Definitions of the technical terms used in this SOP are in Section 3.) The nephelometer is typically calibrated to read zero when filled with particle-free air, so the readings are proportional to light scattering by particles b_{sp}. A span gas, which has a larger scattering coefficient than air, is used to adjust the span of the nephelometer so the b_{sp} data are recorded directly in engineering units of m^{-1}.

Field measurements have shown that nephelometer measurements of b_{sp} correlate well with fine particle concentrations ($PM_{2.5}$) (see, for example, Waggoner and Weiss, 1980; Waggoner et al., 1981; White et al., 1994; Richards et al., 1999; Adhloch 1999). The influence of the coarse particle fraction of PM_{10} on b_{sp} is smaller for two reasons: (1) coarse particles scatter less light per unit mass than do fine particles, and (2) because of the truncation error described in Section 6.1, the nephelometer does not fully respond to light scattering by coarse particles.

The nephelometer does not respond to light absorption by gases or particles. However, when it is hazy, the dominant cause visibility impairment light scattering by fine particles (U.S. Environmental Protection Agency, 1979). Therefore, nephelometer measurements provide a good measure of visibility impairment by haze. If the nephelometer has a size selective inlet, large particles, including drizzle, fog, and snow can be excluded so they do not interfere with the measurement of light scattering by particles smaller than the inlet cutpoint. On the other hand, nephelometers can be designed to admit fog or cloud particles into the scattering volume so the instrument signal includes light scattering by these particles (Molenar, 1997).

1.2 Objectives Light-Scattering Measurements during CRPAQS

The California Regional $PM_{10}/PM_{2.5}$ Air Quality Study (CRPAQS) is a multi-year program of meteorological and air quality monitoring, emission inventory development, data analysis, and air quality simulation modeling. CRPAQS objectives are to: (1) provide an improved understanding of emissions and dynamic atmospheric processes that influence particle formation and distribution; (2) develop and demonstrate methods useful to decision makers in formulating and comparing candidate control strategies for attaining the federal and State PM10/PM2.5 standards in central California; and (3) provide reliable means for estimating the impacts of control strategy options developed for $PM_{10}/PM_{2.5}$ on visibility, air toxics, and acidic aerosols and on attainment strategies for other regulated pollutants, notably ozone.

The overriding purpose of the light-scattering measurements during CRPAQS is to provide a cost-effective method of improving the spatial and temporal resolution of the estimates of the $PM_{2.5}$ concentrations. Questions to be answered include: Are events with elevated $PM_{2.5}$ of short or long duration (i.e. nearby or distant emitter), do they occur at more than one site, do they have directionality, and are they related to wind speed? The answers to these questions will be semi quantitative.

The next level purpose is to better quantify contributions to $PM_{2.5}$ mass from these different phenomena, and if they can be identified, specific sources based on temporal and spatial resolution of light scattering rather than chemical composition.

The final purpose is to determine the extent and intensity of haze and how it varies throughout the region and within sub-regions.

2. SUMMARY OF METHOD

Figure 2-1 shows the internal parts of the Radiance Research Model 903 integrating nephelometer. These parts are enclosed in a cylinder, which is only partly shown. Beuttell and Brewer (1949) first proposed this measurement geometry, which is used by all integrating nephelometers. The scattering volume is illuminated from the side by a diffuse light source. The photomultiplier detector views a dark trap through a conical scattering volume defined by a series of baffles with circular holes in them. The baffles prevent the photomultiplier from viewing any surface, other than the internal span calibration chopper, that is illuminated by the light source. This geometry is used because the light falling on the photomultiplier is very nearly proportional to the light-scattering coefficient of the air sample in the scattering chamber, which is a measure of the total amount of light scattered into all angles by the air sample. The nephelometer processes these data to subtract light scattering by air to obtain a measure of b_{sp}. More information on the Radiance Research Nephelometer is presented in Section 8 and on the interferences in the measurement of b_{sp} in Section 6.

The Radiance Research Nephelometer is computer controlled. It automatically converts the measured voltages to engineering unit data and stores these in memory. The engineering unit data are periodically dumped to a computer in a format that is easily imported into spreadsheets or other programs for editing and analysis. In CRPAQS, 5-min average b_{sp} values were recorded by the nephelometer as well as the temperature and relative humidity measured by sensors within the instrument.

M903 Optical Design

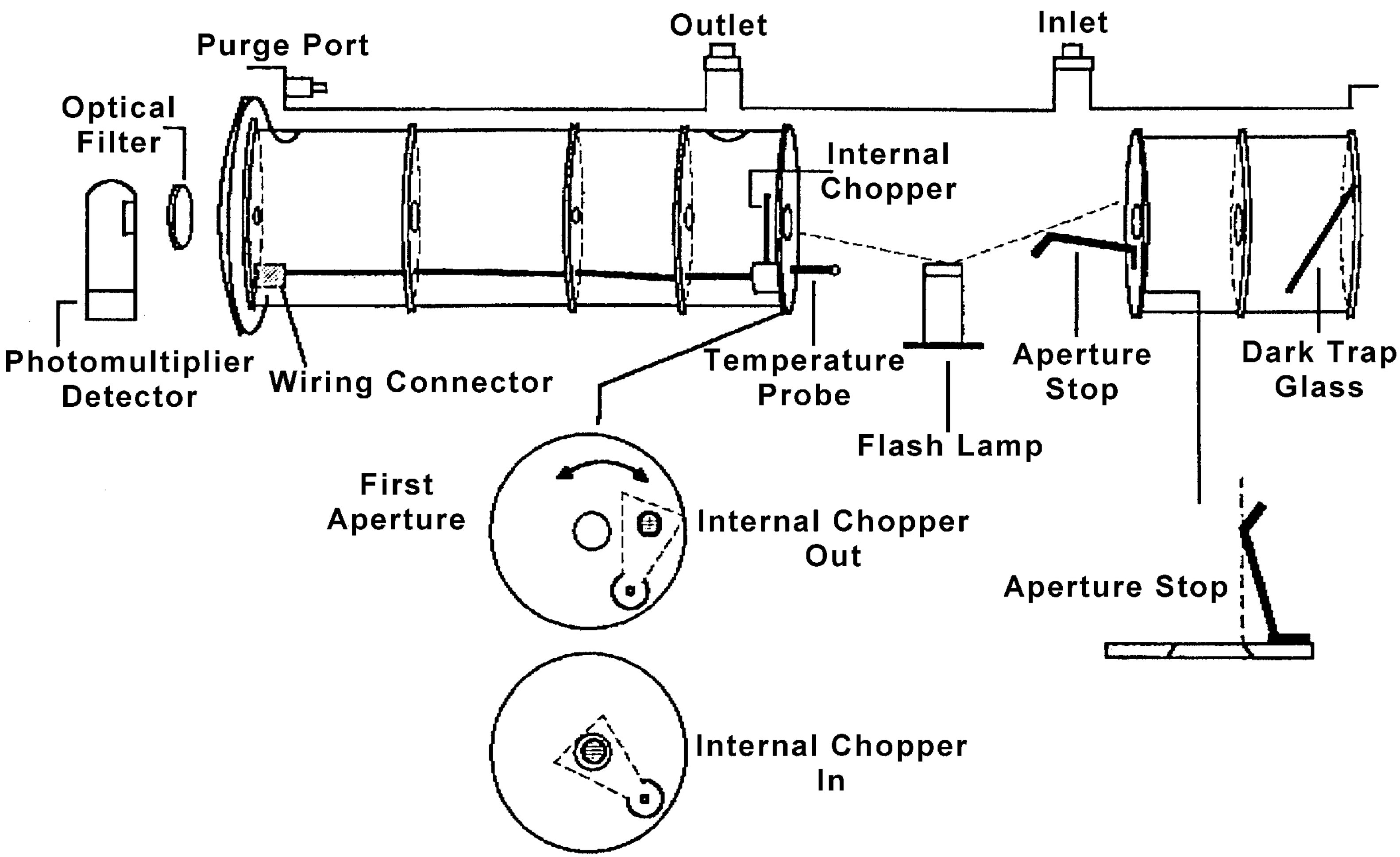

Figure 2-1. The geometry of the Radiance Research M903 integrating nephelometer.

3. DEFINITIONS

Table 3-1 contains definitions of the terms and abbreviations used in this SOP and also terms and abbreviations used in the analysis and interpretation of data from integrating nephelometers.

Table 3-1. Definitions.

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Word	Abbreviation or Acronym	Definition Bold words are defined in this table.
Aerosol		A mixture of **particles** suspended in a **gas**. The particles may be l**iquid, solid** or a mixture of liquids and solids.
Coarse particles		**Particles** in the atmosphere larger than 2.5 µm diameter. This term is sometimes used to indicate the fraction of **PM_{10}** larger than 2.5 µm (i.e., particles with diameters between 2.5 and 10 µm), but can also be used to indicate the concentration of all particles in the atmosphere larger than 2.5 µm.
Elemental carbon	EC	Chemical forms of carbon in which concentrations of other elements are relatively small, e.g., graphitic carbon. Elemental carbon particles absorb light efficiently, have a black appearance, and are sometimes called **black carbon**.
Fine particles		**Particles** in the atmosphere smaller than 2.5 µm (see $PM_{2.5}$).
Fugitive		Fugitive emissions are unintentional emissions. Emissions from an automobile tailpipe are not fugitive emissions because the tailpipe was designed to release emissions, while dust from tires on the road are fugitive emissions because tires were not intended to cause dust.
Gas		One of the three **states of matter.** A gas has neither a definite volume nor a definite shape. Like liquids, gases are fluids and assume the shape of their container. Unlike liquids, they will expand to fill any container, regardless of its size. Air is a gas.
Haze		Suspension in the atmosphere of minute particles that are not individually seen but nevertheless reduce visibility.
Integrating nephelometer		An instrument that measures **light scattering** in an air sample. The illumination and light detection geometry are designed so the instrument signal is approximately the integral of light scattering into all angles.
Light absorption		A process that absorbs light when it interacts with matter and converts the energy into heat.
Light absorption coefficient		The component of the **light-extinction coefficient** due to light absorption.

Table 3-1. Definitions.

Word	Abbreviation or Acronym	Definition Bold words are defined in this table.
Light extinction		The sum of **light scattering** and **light absorption**. A beam of light passing through matter is weakened by light extinction.
Light extinction coefficient		The rate of change with distance of a collimated beam of light caused by light scattering and light absorption. For example, light scattering by particle-free air attenuates a beam of green light by 1 percent per kilometer, so the light-extinction coefficient of particle-free air is 0.01 km^{-1} or 10 Mm^{-1}.
Light scattering		A process that changes the direction of travel of light when it interacts with matter.
Light scattering coefficient		The component of the **light-extinction coefficient** due to light scattering.
Light scattering efficiency		The light-scattering coefficient divided by either the mass or volume concentration. The light-scattering efficiency on a mass basis has dimensions of area per mass and is a measure of the amount of light scattered per unit mass of particles.
Liquid		One of the three **states of matter.** A liquid has a definite volume but no definite shape; it is a fluid and flows to the shape of the containing vessel. Liquid **particles** suspended in a **gas** assume a spherical shape.
Particle		A minute portion of matter. Particles may be **liquid**, **solid**, or a combination of liquids and solids.
Particulate		An adjective indicating that a substance is in the form of **particles**. Careful linguists discourage the use of this word (or its plural) as a noun.
Particulate Matter	PM	**Particles** in the atmosphere; one of the six **criteria pollutants**.
	$PM_{2.5}$	**Particulate matter** in particles smaller than 2.5 µm diameter. Beginning in 1997, the federal standard for **PM** was modified to regulate $PM_{2.5}$ concentrations as well as $\mathbf{PM_{10}}$.
	PM_{10}	**Particulate matter** in particles smaller than 10 µm diameter. Beginning in 1987, the federal standard for **PM** was modified to regulate PM_{10} concentrations.
Phase		**State of matter**. Chemical **species** can exist in the **gas**, **liquid**, or **solid** phases.
Primary particles		**Particles** whose chemical form has not been significantly altered while in the atmosphere; their chemical properties are much the same as when they were emitted.
Rayleigh scattering		Lord Rayleigh developed the first theory for **light scattering** by air molecules, so light scattering by particle-free air is often called Rayleigh scattering.

Table 3-1. Definitions.

Word	Abbreviation or Acronym	Definition Bold words are defined in this table.
Regional haze		**Haze** from many sources that has been mixed so the effects of individual sources are no longer identifiable. If the haze is localized to an urban area, it is called an **urban haze** instead of a regional haze.
Relative Humidity	RH	A measure of the amount of water vapor in the atmosphere. It is equal to the fraction or percentage of the amount of water vapor the atmosphere would contain at that temperature if it were saturated, i.e., in equilibrium with liquid water.
Secondary particles		**Particles** formed in the atmosphere from gases. Examples are **ammonium sulfate** and **ammonium nitrate** particles.
Solid		One of the three **states of matter**. Solids have both a definite volume and a definite shape.
Span gas		A gas with a higher light-scattering coefficient than air used to obtain an upscale reading from an **integrating nephelometer** during a span calibration.
Species		Chemical species include both chemical elements and chemical compounds. One chemical element or one chemical compound are examples of a chemical species.
Urban haze		**Haze** in an urban area due to multiple sources.
Urban plume		**Urban haze** transported downwind to form a **plume** that can be shown to have its origins in an identifiable urban area.

Figure 3-1 shows the relationships between the components of light extinction. Light extinction is caused by light scattering and light absorption. The light-extinction coefficient (b_{ext}) gives a measure of the strength of light extinction and is defined in Table 3-1. The light-scattering coefficient (b_{scat}) and light-absorption coefficient (b_{abs}) provide a measure of light scattering and light absorption, respectively. As indicated in Figure 3-1, the light-extinction coefficient is the sum of the light-scattering and the light-absorption coefficients.

Each of these coefficients can be further subdivided as shown in Figure 3-1 to indicate the relative contribution of gases and particles to scattering and absorption. Each coefficient in Figure 3-1 is the sum of the coefficients with lines leading to it from below.

Light scattering by particles (b_{sp}) is the dominant cause of impaired visibility and is the quantity measured by the Radiance Research nephelometer. Light scattering by gases (b_{sg}) is sometimes called Rayleigh scattering and is the scattering caused by particle-free air. Rayleigh scattering can be calculated from the air density, which in turn can be calculated from the ambient temperature and pressure. Light absorption by particles (b_{ap}) is mostly caused by elemental carbon and is measured by the Aethalometer. Light absorption by gases (b_{ag}) is mostly caused by nitrogen dioxide (NO_2) and can be calculated from measured NO_2 concentrations. Each of these four components of light extinction can be determined from measurements made at the CRPAQS Anchor Sites.

As indicated in Figure 3-1, b_{scat} is the symbol used for the combined light scattering by particles and gases, while b_{sp} is used for light scattering by particles alone. The Radiance Research manual and the LCD display screens on the Radiance Research nephelometer use a confusing mixture of abbreviations (Radiance Research, 1999). In CRPAQS, the nephelometer is calibrated to read zero when filled with particle-free air so the nephelometer readings are a measure of b_{sp}. Nephelometers can be calibrated to read b_{sg} when filled with particle-free air, in which case the readings are a measure of b_{scat}. It has been recommended to the manufacturer that the LCD screens on the Radiance Research nephelometer always use the symbol bs for the measurement and that the manual indicate that the interpretation of the bs readings depends on how the instrument is calibrated.

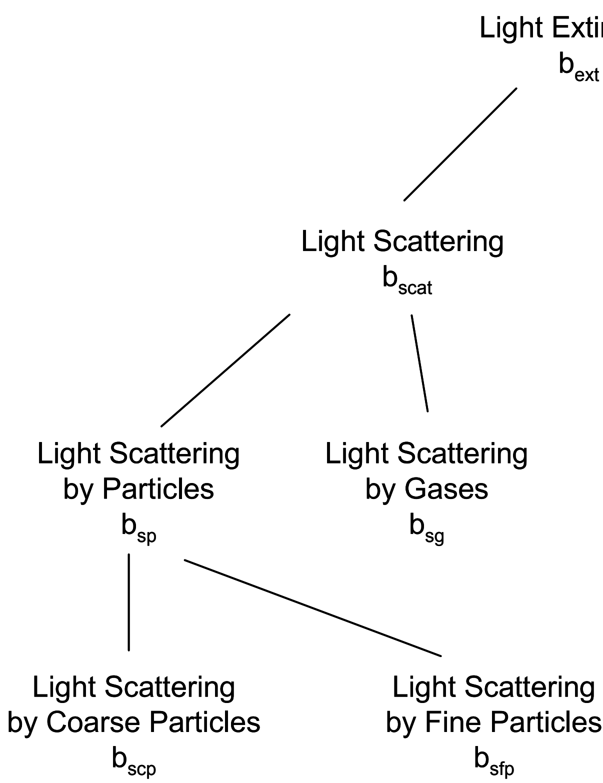

Figure 3-1. Diagram showing the relation between the components of light extinction.

4. HEALTH AND SAFETY WARNINGS

The health and safety hazards associated with operating an integrating nephelometer are small. The most important hazards are listed in decreasing order of importance.

- Asphyxiation by calibration gas. All gases used for span calibration of integrating nephelometers are heavier than air and are capable of displacing the oxygen in a vehicle or workspace. This can occur if an accident breaks or opens the valve that closes the gas cylinder or a large flow of the calibration gas is used in a poorly ventilated space. Care should be taken to transport and store calibration gas cylinders in a manner that minimizes the possibility of damaging or opening the gas cylinder valve. Gas cylinders that do not have a built-in base should be secured from tipping over.

- High voltages. The integrating nephelometer contains high-voltage circuits. The instrument should be unplugged from the power source and capacitors allowed to discharge before servicing the instrument.

5. CAUTIONS

The cautions for the Radiance Research M903 Integrating Nephelometer are the same as for any electronic air-quality monitoring instrument that samples particles. The operator should read and understand both the instrument manual and this SOP.

The most likely cause of data loss is not restarting the data acquisition after dumping the data from the nephelometer memory. Data acquisition and averaging is stopped when the “s” command is sent to the nephelometer via the serial port. This is the first step required to dump the data. Data acquisition and averaging does not resume until either “q <Enter>” command is sent or the nephelometer is turned off and on. When data acquisition is stopped, the time displayed on the **Main Screen** does not advance. Operators should always be sure the displayed time is advancing properly before leaving the nephelometer.

6. INTERFERENCES

The interferences in the measurement of light scattering by particles can be divided into (1) interferences in the measurement of light scattering by particles as they exist in the nephelometer sample volume, and (3) differences between the light scattering properties of the particles in the sample volume and the particles in the ambient air.

6.1 Interferences in the Measurement

The following interferences affect the ability of the integrating nephelometer to measure the light scattering properties of the air sample as it exists in the sampling chamber of the instrument.

Truncation Error. As shown in Figure 2-1, the integrating nephelometer cannot measure light scattering at all angles. It is necessary to prevent the light source from shining on either the light detector or the dark trap, so light scattering by the sample air cannot be measured at angles near 0 and 180 deg. The truncation error has been described and its effects calculated by Ensor and Waggoner (1970), Heintzenberg and Quenzel (1973), Rabinoff and Herman (1973), Heintzenberg (1978), Hasan and Lewis (1983), and others.

The truncation error is present both during the calibration of the nephelometer with particle-free gases as well as during measurements of light scattering by particles. The error tends to cancel out for measurements of light scattering by submicron particles, because they scatter only a slightly larger fraction of the total scattering into angles near 0 and 180 deg than do the calibration gases. As particles become larger, a larger fraction of their scattered light is in angles near 0 and 180 deg, and the truncation error increases. For coarse particles (between 2.5 and 10 µm diameter), it has been determined that the light scattering measured by the nephelometer is approximately half the total light scattering (White et al., 1994).

Wall Scattering. Wall scattering is the name given to the signal caused by stray light within the nephelometer. Light from the lamp can be reflected from the walls of the nephelometer and illuminate the dark trap and the edges of the baffles that define the field of view of the light detector. This light can then be reflected toward the light detector.

Calibrating the nephelometer to read zero when filled with particle-free air accounts for the wall scattering present at the time the calibration was performed. If the wall scattering were constant, this scattering would be subtracted from all subsequent measurements. However, dust can accumulate on the walls of the nephelometer, the dark trap, and the edges of the baffles and increase the stray light. Thus, the wall scattering tends to increase gradually over time. This process can be monitored by periodically filling the nephelometer with particle-free air and measuring any increase in the zero signal.

If a spider should spin a web in the scattering volume, the zero signal can increase dramatically and swamp the light-scattering signal by particles. If this happens, it is necessary to open the nephelometer and clean out all webs before the collection of valid data can resume. Spider webs are variable enough and move about in the airflow, so it is not practical to cancel their effect by adjusting the nephelometer zero.

Two approaches are commonly used to account for the gradual increase in wall scattering between times when the dark trap is cleaned. One is to adjust the nephelometer zero to keep the particle-free air readings near zero. The other is to measure and record the zero readings and to account for the gradual increase in wall scattering during data processing. The latter procedure is recommended during CRPAQS. If the zero is frequently adjusted, a faulty calibration can introduce unknown errors into the data. Also, no record of the drift in the zero with time is available. If the zero is not adjusted, the calibration data provide a record of the nephelometer performance that can be analyzed to determine the nephelometer performance. Also, the calibration data provide an historical record of the nephelometer performance.

Variations in the Temperature, Pressure, and Gas Composition of the Atmosphere. The amount of light scattered by particle-free air varies with the density and composition of the air. Water molecules have a different scattering coefficient than nitrogen and oxygen molecules. Therefore, the signal that should be subtracted from the total signal measured by the nephelometer to determine the light scattering by particles varies with the temperature, pressure, and relative humidity.

The effect of variations in the temperature and pressure can be accounted for by including temperature and pressure sensors in the nephelometer and using these readings to calculate the amount of light scattering by air to be subtracted from the measured signal. Three nephelometers used in CRPAQS (serial numbers 0192, 0193, and 0194) have both temperature sensors and automatically calculate this correction.

By far the largest error is introduced by variations in temperature. All Radiance Research nephelometers used in CRPAQS (except at the Fresno Supersite) have temperature sensors in the scattering chamber and use this measured temperature to calculate the amount of light scattering by air to be subtracted from the total measured signal. Nephelometers that do not have a pressure sensor should have an ambient pressure appropriate for the site elevation entered manually (see "Set Local Pressure Screen" in Section 9.1). This pressure is used in the calculation by the nephelometer of the amount of light scattering by air. If the local pressure is set correctly at each site, it should not be necessary to change the zero calibration of the nephelometer if it is moved to a site with a different elevation.

<u>Calibration Error</u>. The nephelometer is calibrated by filling it first with particle-free air and then with a span gas having a higher light scattering coefficient. The temperature and pressure in the scattering chamber must be known (or estimated) to calculate the calibration gas density and scattering coefficient. These two points, combined with the linear response of the nephelometer, provide the calibration.

Errors can be introduced by incorrect calibrations. The most common errors are failing to displace all ambient air in the scattering chamber with the calibration gas, failing to filter the calibration gas to remove all particles, and incorrect determinations of the temperature and pressure of the calibration gas.

6.2 Sample Air Modification

All instruments that draw air into a sample volume modify the sample air to some extent. In the case of integrating nephelometer measurements, some sample air modification is intentional and beneficial. For example, fog and snow can be excluded from the nephelometer to minimize meteorological effects on air quality measurements. Also, size selective inlets may be used to define the particle size range sampled by the nephelometer.

<u>Sample Air Heating</u>. The lamps and electronics of most nephelometers generate heat, which heats the air flowing through the sample chamber. This heating lowers the RH of the sample air, and thereby tends to decrease the amount of absorbed water in the sampled aerosol particles. The light scattering by the sampled particles is decreased for two reasons: (1) the loss of water from the particles decreases their volume, so there is less aerosol to scatter light, and (2) the loss of water decreases the size of the aerosol particles, which decreases their light scattering efficiency.

The Radiance Research nephelometers are designed to minimize inadvertent heating of the sample air. The light source is a flash lamp, which generates little heat, and the electronics are in a separate housing. Therefore, this nephelometer is capable of measuring light scattering at conditions that are very close to ambient. This permits minimizing the volatilization of nitrates, organic species, and water from the ambient aerosol during measurement.

Measurements at ambient conditions can cause unwanted interferences when it is foggy or when an incursion of warm, humid air increases the dew point above the temperature of the nephelometer hardware. In the latter case, water can condense on the dark trap and other optical components and cause large signals unrelated to light scattering by ambient particles. When it is foggy, the light scattering signals can become very large and have little relation to filter measurements of PM concentrations.

To avoid instrument problems and unwanted effects at very high relative humidity, the CRPAQS nephelometers are equipped with a sample-air inlet heater and a controller that applies heat only when the RH is high. The heater and controller are described in Section 8.2. In initial experiments, the RH threshold was set to 85%. It was found that at this relatively high RH, small differences in the calibration of the RH sensors in the nephelometer and in the setting of the controller made large differences in the light scattering signal. At 85% RH, the amount of water in the aerosol varies rapidly with variations in the RH.

Because the purpose of the CRPAQS nephelometer measurements is to provide a surrogate for the $PM_{2.5}$ filter measurements, the threshold for the controller was set at approximately 65% RH. Thus, sample air heating begins when the RH reaches about 63% and increases with increasing RH. When the RH is very high, the heater applies enough power to limit the RH reading to about 70%. In this RH range, the aerosol contains some liquid water, which tends to stabilize the particulate nitrate. It is expected that this setting of the heater controller will enable measurement of light scattering by particles at ambient conditions when the RH is less than 65% and also a heated measurement that correlates well with filter measurements of $PM_{2.5}$ when the RH is greater than 65%.

During the early part of CRPAQS, the relative humidity (RH) sensor was in a fitting on the sample air inlet to the scattering chamber. This configuration allowed the sample airflow to be inadvertently cooled in the scattering chamber, with the result that RH values higher than intended could occur. The configuration was modified in December 2002 by reversing the airflow through the scattering chamber so the RH sensor was on the outlet and by adding thermal insulation to the scattering chamber. Then the heater controller applied heat as necessary to keep the RH at the outlet of the scattering chamber at the intended value. An intercomparison performed after the end of the CRPAQS field measurements evaluated the effect of this change in the operating configuration on the measured b_{sp} values (Richards, 2002)

<u>Particle Sampling Efficiency</u>. Not all particles in the ambient air pass through the sample air inlet system to reach the scattering chamber of the nephelometer. Particle losses increase with increasing particle size, and become severe for particles larger than 10 to 15 µm. Most light scattering is caused by fine particles, which tend to have small losses in properly designed inlet systems. Therefore, errors due to removal of particles by the sample air inlet system are small in

properly designed systems. Uncertainties caused by inefficient sampling of coarse particles can be eliminated by the use of a size selective inlet (see next paragraph).

Size Selective Inlet. Nearly all particle-sampling procedures use a size selective inlet to control the range of particle sizes that reach the collection device or measurement instrument. Nephelometry is unusual in that monitoring networks commonly do not use a size selective inlet on integrating nephelometers. This aberration has been discussed (Richards, 1994). White et al. (1994) have demonstrated the benefits that can by obtained by using size-selective inlets on nephelometers. Size selective inlets can also remove fog droplets from the sample airflow, permitting the measurement of the interstitial aerosol (Watson et al. 1996). Removing the fog droplets also helps protect the nephelometer optics from liquid water.

Initially, size selective inlets with a 2.5-µm cutpoint were recommended for the CRPAQS light scattering measurements. They were omitted to help keep the project costs within budget.

7. PERSONNEL QUALIFICATIONS

Operation and maintenance of the Radiance Research M903 Integrating Nephelometer does not require any skills or qualifications other than those routinely expected of technicians who operate and maintain air quality instrumentation in the field. As indicated in the quick start instructions in Section 11.1, if the operating parameters are correctly set at the end of the acceptance test, the nephelometer will begin collecting valid, self-calibrated data when it is placed in the outdoor shelter, plugged in, and turned on. As with all instruments, the technician must become familiar with the instrument and its operation as described in the instrument manual and this SOP and must keep good records of instrument operations, conditions that may affect the data, and the data acquired from the nephelometer.

8. APPARATUS AND MATERIALS

8.1 Radiance Research M903 Nephelometer

The Radiance Research M903 Nephelometer uses the integrating nephelometer geometry (Beuttell and Brewer, 1949) shown in Figure 2-1 to measure the light-scattering coefficient at an effective wavelength of 530 nm. It is a modern version of an instrument first designed by Ahlquist and Charlson (1967). General descriptions of integrating nephelometers have been published by Ruby and Waggoner (1981), Ruby (1985), and Anderson et al. (1996). The Radiance Research Nephelometer is small (56 cm high with a 13 x 17 cm footprint), light weight (less than 3 kg), uses about 3 watts of either 110 V AC or 12 V DC power, and is computer controlled. **Figure 8-1** shows a photograph of this nephelometer in the environmental shelter designed for CRPAQS. The flash lamp light source causes minimal sample air heating. Measurements between flashes and with the internal chopper shown in Figure 2-1 enable automatic zero and span calibration. The nephelometer was equipped with a temperature sensor in the scattering chamber and an RH sensor in the sample air inlet. The pressure sensor and a size-selective inlet were omitted to keep the instrument cost within budget.

Figure 8-1. Photograph of the Radiance Research M903 Nephelometer installed in the environmental shelter designed for CRPAQS.

The nephelometer is calibrated to read zero when filled with particle-free air. The instrument is programmed to calculate and store 5 min average readings of b_{sp} (light scattering by particles). The electronics calculates and subtracts light scattering by air using the manually entered pressure and the temperature measured in the scattering chamber. Five-minute averages of temperature, RH, pressure setting, and calibration signal are recorded with the b_{sp} data. The nephelometer holds 12 days of 5 min averages in battery-supported RAM. At sites without a data logger, these data are periodically dumped to a laptop computer and marked to provide the option of not including them in the next data dump. At sites with a data logger, analog outputs are recorded continuously and digital data are dumped daily. Because of the computer control built into the nephelometer, a wide range of other operating modes can be selected.

The nephelometer measures light-scattering coefficient values between about 1 Mm^{-1} and more than 1 km^{-1}. The lower detectable limit of less than 1 Mm^{-1} is 1/10 of light scattering by particle-free air. The absolute temperature is measured by a thermister with an accuracy of 0.2% and the RH by a Vaisala sensor with an accuracy of about 2 percentage units, provided the RH sensor has been calibrated. When the RH sensors are not calibrated, the readings can differ among nephelometers by 3 or 4 percentage units, but the offset between nephelometers remains constant to within about 2 percentage units. The interferences in the Radiance Research nephelometer measurements are described in Section 6 and are the same as for other integrating nephelometers (Ruby and Waggoner, 1981; Ruby, 1985; Anderson et al., 1996). Recent measurements have shown excellent correlations between both ambient and heated nephelometer measurements and $PM_{2.5}$ in the San Joaquin Valley during wintertime conditions (Richards et al., 1998, 1999; Adhloch et al., 1999). The aerosol composition is different during summer, so it is expected that different correlations will apply during the dry season.

The Radiance Research manual lists the instrument specifications (Radiance Research, 1999).

8.2 Sample Air Heater and Controller

The sample air inlet of the nephelometer is equipped with a heater with a low thermal-mass heating element from a hair dryer. The user can set the threshold RH of the heater controller. During CRPAQS, the controller was adjusted so no heat was applied below about 63% RH and the RH reading was limited to about 70% in the absence of fog. The applied heat increases gradually with increasing RH sensor signal, so the heating does not oscillate. Calculations indicate that RH readings in the 70% to 80% range cause more than enough power to be delivered to the heater to evaporate a fog with liquid water content of 1 g/m^3. This design of heater and controller permits measuring light scattering at ambient conditions for RH values below about 63% while protecting the instrument optics from high RH and foggy conditions. The sample air inlet of the heater was fitted with a bug screen made from 56-mesh stainless steel wire cloth.

See Section 6.2 for a discussion of the rationale for selecting an RH threshold with a nominal value of 65%.

8.3 Environmental Shelter

The environmental shelter is shown open in Figure 8-1 and closed in **Figure 8-2**. It was constructed from painted, ½ inch thick marine plywood and has an inside width of 15 inches (38 cm), depth of 12 inches (30.5 cm) and height of 25 inches (63 cm) at the back. The roof overhangs the sides and is sloped so the inside height is greater in the front than in the back. The sides of the enclosure extend approximately 4 inches (10 cm) below the floor, so the sample air inlet and outlet in the bottom of the enclosure are shielded from rain.

The front of the enclosure is completely removable. At some sites were the enclosures are not locked, a hasp behind the bottom of the door secures the door. Otherwise, the door is secured by a screw eye that fits through a slot in the door. Heavy, brass, resettable combination locks are provided for the locked sites. When a padlock is used, the screw eye can be turned to adjust how tightly the door is held closed when the lock is in place.

Figure 8-2. Photograph of the environmental shelter when closed. The peg holding the door closed can be replaced with a padlock.

Sample air enters the shelter through a screen-covered hole in the floor of the shelter and is conducted to the top of the shelter by a 2-in. diameter ABS plastic pipe. Sample air is exhausted from the shelter through a screened opening in the floor of the shelter by a ventilating fan rated at 32 cfm. The inside volume of the shelter is approximately 2.5 ft^3. If the flow impedance caused by the screens reduces the airflow through the shelter to half the nominal flow or 16 cfm, the air turnover time is about 1/6 min or 10 sec.

The shelter contains a surge suppressor with six receptacles. It can be removed from the wall of the shelter by lifting it upwards and replaced by hooking it over the screws in the wall of the shelter and pushing down. Three of the receptacles on the surge suppressor are used by the fan described above, the nephelometer, and the sample air heater. The shelter has a hook behind the surge suppressor where the nephelometer power supply can be hung, rubber feet to raise the nephelometer above the floor so moisture will not accumulate between the nephelometer and the floor, staples that allow the nephelometer to be secured to the shelter by a tie wrap, and a staple that can be used to secure the tube for the calibration gases. The heater controller is mounted to the side of the shelter above the surge suppressor.

The shelter door has a weather strip to minimize moisture entry. The hole for the power cord for the surge suppressor is filled with flexible foam that can be removed. The foam is replaced by winding it around the power cord and stuffing it in the opening.

The shelter installation is described in Section 9.5. The parts in the shelter are easily replaced. If the inlet screen becomes broken, the ABS pipe coupling below the bottom of the shelter can be pried off and a pipe unit with a new screen obtained from the factory. Sometimes, the ventilating fans chatter when they are first turned on. The chatter can be stopped by switching the power off and then on again.

8.4 Calibration Gases

It is recommended that the nephelometer be calibrated with two gases, and that one of the gases should be particle-free air obtained by passing ambient air through a filter. The other gas should have a larger light-scattering coefficient than particle-free air. The Radiance Research manual (Radiance Research, 1999) lists the light scattering properties of air and five other calibration gases. The advantages of CO_2 and Freon 134a, also known as SUVA, are discussed in Section 10, where the procedures for using these gases to calibrate a nephelometer are described.

8.5 Data Acquisition

<u>Satellite Sites</u>. The monitoring data will be acquire from the nephelometers at the satellite sites by using a straight-through serial cable (not a null modem cable) to connect the serial port of the nephelometer to a COM port of a laptop or other computer. Any communication software can be used to communicate with the nephelometer, including HyperTerminal, which is included in the Microsoft Windows operating system. The baud rate in the communication software should match the baud rate displayed in the **Serial Port Adjust Screen** described in Section 9.1. The other communication parameters are no parity, eight bits, and one stop bit.

When the nephelometer is averaging and recording data, it sends a data record to the serial port every flash. When communication is established with the nephelometer, these data are displayed on the computer screen. The command “s” stops data acquisition and displays a menu of options described in Section 7.2 of the manual (Radiance Research, 1999). (Either upper or lower case can be used for commands.) The options include dumping either unmarked data or all data from the nephelometer memory, marking the data in memory, setting the clock and other parameters, etc. The command “q <Enter>” exits the menu and causes data acquisition to resume. The operator must not forget to enter the “q” command at the end of a communication session. If this step is forgotten, no data will be recorded in the nephelometer memory until either the nephelometer is turned off then on or the “q” command is entered.

The nephelometer memory can hold 12 days of data. The memory operates in a loop so the newest data over writes the oldest data. When the data are dumped to a computer, the data in the nephelometer memory can be marked. If only unmarked data are dumped each visit, the data files from each site visit can be concatenated without editing to produce continuous data records. If it is found that the data from one visit are lost or corrupted, it is possible to dump all 12 days of data from the nephelometer memory. Thus, if the discovery of corrupted data is made soon enough and the site is visited quickly, all data can be recovered. If it is suspected that the nephelometer is not operating properly, all data in nephelometer memory should be dumped in the verbose format using the "a <Enter>" command. The verbose data contain diagnostic information that can help evaluate malfunctions.

The recommended procedure for the satellite sites is to:

- Visit the sites to view the nephelometer status and dump data. No more than 12 days (to the minute) should elapse between visits.
- Use a straight through (not null modem) serial cable to connect the serial port on the computer to the serial port on the nephelometer.
- Use a communication program, such as HyperTerminal (which is built into Windows) or Procomm to communicate with the nephelometer. When communication is established, a data record should show on the computer screen every flash.
- Enter an "s" to bring up the menu in Section 7.2 on page 17 of the Radiance Research manual. Then turn on the data capture in the communication program.
- Dump all unmarked data in the short format using the "s <Enter>" command. When the dump is complete, turn off the data capture in the communication program.
- Mark all data in memory using the "m <Enter>" command and responding "y" and then "n" to the prompts. A displayed "ok" message will confirm that the data have been marked.
- The time of the nephelometer clock is displayed on the computer screen using the "t <Enter>" command. Give this command at a known time on the reference clock and enter both the time of the reference clock and the nephelometer clock in the site visit notes. Calculate the amount of time by which the nephelometer clock is fast or slow. It is recommended that the time of the reference clock be set using the time at www.time.gov on the Internet or other time standard. If the nephelometer clock is more than 30 seconds in error, reset the nephelometer clock by the command "t hhmm <Enter>." The "t hhmm" should be entered in the computer ahead of time, and the <Enter> key pressed on the second when the time is correct.
- Be sure to exit the data dump menu "q <Enter>" and verify that the nephelometer clock is advancing and the data reading is changing. (The nephelometer will not log data in its memory if this step is forgotten. Before leaving the site, double check that the nephelometer clock is advancing.)

Anchor Sites. Data will be recorded at the anchor sites in two ways: (1) analog data will be recorded on the data logger at each site so the light scattering readings are continuously available along with the data from the other measurements at the site, and (2) the digital data will be automatically dumped daily by the data logger using the commands described above. It is recommended that the digital data be the source of the archive data record.

9. SITE AND EQUIPMENT PREPARATION

The first step in the nephelometer acceptance test is to review and record the nephelometer settings as described in Section 9.1. The instructions indicate that during this review, some settings should be left as set by the factory and others should be changed to conform with the settings to be used during CRPAQS.

9.1 Nephelometer Settings

It is recommended that a permanent record of the nephelometer setting be started at the beginning of the acceptance test. This record will show the nephelometer settings when received from the factory, the changes in the settings made during the acceptance test (if any), and any changes in the settings made during the course of the field study. This record will include the nephelometer model and serial number, the version of the software installed, etc. Key parameters in this record include the integers that indicate the zero and span settings and the photomultiplier voltage. It is likely that the clock in the nephelometers will be reset every few weeks. Keeping a record of the clock times is important only during the field monitoring.

When the nephelometer is received and unpacked, it should be plugged in and turned on as described in the quick start instructions in Section 11.1. The **Display** toggle switch should be used to step through the panel display screens to verify that the instrument settings are correct and to view key parameters that should be recorded. The information in each screen to be verified and/or recorded is listed below. The section number in the Radiance Research Operation Procedures manual for the M903 Nephelometer (Radiance Research, 1999) where each screen is described is indicated. The items showing in each screen are referred to by the numbers in the Radiance Research manual (Radiance Research, 1999).

Main Screen. (Manual Section 5.3.2). This is the default screen, which is automatically displayed when the nephelometer is turned on. The date and time (number 4) should be verified, and if necessary, should be reset at some later time when it is convenient using the serial connection to a computer described at the end of this Section. Display item number 3 should indicate that the nephelometer is operating in the Log mode with a 5 min averaging time. If not, the mode should be changed in the following screen. The averaging time is set using the serial connection to a computer described at the end of this Section.

Mode Change Screen. (Manual Section 5.3.3) Moving the **Item** switch to the **Slow** position cycles through the data acquisition modes. The log mode should be selected. This is the only mode in which data averages are recorded in the nephelometer memory.

Zero Calibration Screen. (Manual Section 5.3.4) It is recommended that the zero calibration setting not be changed (See Section 9.3 below). The 5-digit number in the lower right of the screen (number 4) should be recorded in the permanent records. This number preserves the value of the zero calibration performed at the factory.

Span Calibration Screen. (Manual Section 5.3.5) It is recommended that the span calibration setting not be changed (See Section 9.3 below). The 5-digit number in the lower right of the screen (number 5) should be recorded in the permanent records. This number preserves the value of the span calibration performed at the factory. The value of the span calibrator (number 3) wall scattering (number 4) should also be recorded.

Photomultiplier Adjust and Diagnostic Screen. (Manual Section 5.3.6) The photomultiplier high voltage in the upper right corner of the screen (number 7) should be recorded in the permanent records. This number should not be changed without contacting the factory. The other numbers on this screen vary with the air quality.

As the span chopper changes position, the nephelometer either makes light scattering or span calibration measurements. The greater than symbol at the upper left of the screen indicates which is being measured (numbers 1 and 2). The greater than symbol moves back and forth between the numbers as the span calibration shutter moves back and forth. The number with the greater than symbol is continuously updated while the other number remains constant. Consult Section 5.3.6 of the Radiance Research manual for a description of each of the other numbers and their expected ranges (Radiance Research, 1999).

Set Local Pressure Screen. (Insert to the Manual). The Parameter switch should be toggled to either Raise or Lower to set the pressure to a value appropriate for the site elevation. The correct pressure can be calculated from the formula

$$\text{Pressure} = 1013\ ((288 - 0.0065\ \text{site elevation in m})/288)^{5.256}\ \text{mb}.$$

or it can be looked up from a spreadsheet available from T&B Business Systems that contains these calculations for each site. Nephelometers with Serial Numbers 192, 0193, and 194 contain pressure sensors, so this screen is not available in these instruments and there is no need to enter a pressure manually.

Set Air Rayleigh Scattering Coefficient Screen (Manual Section 5.3.7). THIS SETTING SHOULD NOT BE CHANGED, and should read 1.42e-5. It is the light scattering coefficient for particle-free air at standard conditions and a wavelength of 530 nm. The 16-bit number used to set the coefficient (number 3) should be recorded in the permanent records of the instrument.

Calibration Gas Screen (Manual Section 5.3.8). This screen displays the ratio of the light-scattering coefficient of the calibration span gas to the light-scattering coefficient for particle-free air (Rayleigh scattering). If CO_2 is used as the span gas, this parameter should be set to 2.61 (number one) by setting the value in the lower right of the screen to 00261 (number 2). The value of this entry is only used to calculate the span gas scattering shown as number 2 in the Span Calibration Screen. The value of this entry affects the nephelometer readings only if the span calibration is adjusted to make the measured scattering (number 1) match the span gas scattering (number 2) in the Span Calibration Screen. If that adjustment is not made, the ratio displayed in the Calibration Gas Screen has no effect on the data.

Serial Port Adjust Screen (Manual Section 5.3.9). This screen displays the current baud rate for the serial port and allows that rate to be set at 1200, 2400, 4800, or 9600 baud. A setting of 9600 baud is recommended, unless another setting is required by the computer used to dump the data from the nephelometer memory.

Logo Screen. (Not described in the Manual). This screen indicates the version number of the program loaded in the nephelometer, the program checksum, and the software options as a hexadecimal number. The checksum identifies the exact software installed. All of these numbers should be recorded in the permanent records of the instrument.

It is recommended that the nephelometer typically be operated with the **Main Screen** displayed. This is the default screen, which is displayed when the nephelometer is turned on. To communicate with the nephelometer through the serial port, the straight-through serial cable should be connected to a COM port of a computer as described in Manual Section 7.0 (Radiance Research, 1999). A null modem cable should not be used. The menu described in Manual Section 7.2 should be used to view the setup parameters for the fast, slow and data logger modes. These parameters should be recorded as part of the permanent record of the instrument.

Only the data logger mode will be used for recording data during CRPAQS. The recommended parameter settings for the data logger mode are listed in **Table 9-1** and are viewed by entering Z <Enter> from the main menu. The last parameter, which can be changed by typing H <Enter>in the Log Mode menu, indicates the averaging time period for the measurement. An averaging time of 5 min will be used in CRPAQS so the displayed value should be 133. This parameter should be adjusted if necessary. If any other parameter has a value different from the one indicated in Table 9-1, Radiance Research should be contacted to learn the settings recommended for the nephelometer in question during CRPAQS.

Table 9-1. Recommended parameter settings for the Log Mode.

Type to View Parameter	Recommended Parameter Value	Parameter Description
A	002	Signal filter order
B	002	Calibrator filter order
C	006	Signal averaging time, 2^n flashes
D	006	Calibration averaging time, 2^n flashes
E	040	Flash interval in units of 10 ms
F	035	Signal shutter dwell time in flashes
G	010	Calibrator shutter dwell time in flashes
H	133	Signal averaging time in log mode. Values from 2 to 60 give averaging time in seconds. For averaging times in minutes, add 128 to the number of minutes. The averaging time is displayed in the **Main Screen** when the nephelometer is operating in the log mode.

9.2 Nephelometer Acceptance Tests

For CRPAQS, Air Resource Specialists, Inc (ARS) performed the nephelometer acceptance tests at their Colorado facilities, and then shipped nephelometers to the field for installation (Technical & Business Systems, Inc., 2001). The testing procedures included:

1. If the nephelometer did not have a pressure sensor, setting the ambient pressure was set to a value appropriate for the ARS facility (see the Set Local Pressure Screen paragraph in Section 9.1)
2. The nephelometer was challenged with a particle free (filtered) air reference (see Section 10.3 and Section 10.2 steps 1 and 2).
3. The nephelometer was challenged several times with an up-scale span gas, duPont SUVA 134a refrigerant. The span gas was metered into the nephelometer slowly to prevent condensation in the instrument (see Section 10.3 and Section 10.2 steps 3 and 4).
4. Operation of the heater was verified by introduction of humidified air sufficient to trigger operation of the heating system.
5. Inlet sample flow was verified with a primary flow measurement device.
6. Proper operation of the analog and serial outputs were verified.
7. System documentation was reviewed for completeness and accuracy.
8. The nephelometer pressure (if present), temperature, and relative humidity sensors were checked for accuracy.

9. Acceptance tests were documented on forms developed specifically for the Radiance Research Nephelometer, and are available in both hardcopy and electronic formats.
10. If the nephelometer did not have a pressure sensor, the ambient pressure was set to a value appropriate for the SJV.

9.3 Zero and Span Calibration

The procedures described in Section 10 should be used to determine the zero and span of the nephelometer. Since the loss of monitoring data is not a consideration during the acceptance tests, it is recommended that the calibration gases be left flowing for a long enough period of time that several 5-min averages are recorded for both the zero and the span. At the beginning of CRPAQS, it was recommended that the factory settings for the zero and span not be changed unless two independent calibrations show that the zero is in error by more than 10 Mm^{-1} and the slope is in error by more than 20% when the ambient temperature is below 30°C (86°F). (See the discussion at the end of Section 10.2.)

Analysis of the calibration and audit data from the nephelometers at the satellite sites by Richards et al. (2001) showed that after a few outliers were omitted, the mean zero from all calibrations was 0.4 ± 1.4 Mm^{-1}, where the uncertainty is the standard deviation about the mean. The audit data were essentially identical. Therefore, it is recommended that the factory zero be changed during the acceptance test if the reading for particle-free air differs from zero by more than about 1 Mm^{-1}. These same calibration data gave a ratio of the observed slope to the slope expected for the span gas of 0.99 ± 0.04, and again, the audit data were essentially identical. Therefore, it is recommended that the factory span be changed during the acceptance test if the zero is adjusted or if the ratio of the observed and expected spans differs by more than 5% from unity.

In the preliminary evaluation of the Radiance Research M903 Nephelometer for use in CRPAQS, it was found that the zero did not change significantly with changes in the ambient temperature but that the span calibration did. The nephelometer readings tended to be 10% to 20% low at high ambient temperatures (near 50°C). It is not known whether this temperature dependence will be the same for all Radiance Research Nephelometers used in CRPAQS.

9.4 Site Selection

In the CRPAQS program, site selection was performed by the Field Manager and not by the organizations responsible for the operation of the nephelometers. Therefore, there was no need to include information on site selection criteria in this document. For a description of the CRPAQS site selection process, see Watson et al. (1998).

9.5 Shelter Installation

The shelter is shown in Figures 8-1 and 8-2 and is described in Section 8.3. It is constructed from marine plywood and has a flat back surface. It is expected that most shelters will be mounted to pipes by drilling holes in the back of the shelter and using U-bolts to fasten the shelter to a pole. It is important that the channel iron supplied with the U-bolt be on the outside of the shelter between the shelter and pole so the stress resulting from the U-bolt is supported by the channel iron and not the plywood shelter. The shelter can be mounted on wood poles using wood screws or lag bolts. In all cases, mounting holes in the shelter should be sealed with caulk to minimize the entrance of water and insects.

In CRPAQS the shelters will typically be about 10 m above ground or on a roof. The AC power strip and surge suppressor in the shelter has a 6 ft cord and plug. This will be plugged into a receptacle provided at the monitoring site.

10. INSTRUMENT CALIBRATION

10.1 Introduction

Enclosed integrating nephelometers, including the Radiance Research M903 Nephelometer, are calibrated by filling them first with one and then with another calibration gas with known light-scattering coefficients. Then the light-scattering readings are recorded. During an initial calibration, the zero and span settings stored within the nephelometer are adjusted during the calibration procedure as described in Section 6 of the Radiance Research manual (Radiance Research, 1999). The standard procedure during CRPAQS is to leave the internal calibration settings of the nephelometer unchanged. This approach develops a performance history for each instrument and avoids the possibility that variable calibrations will degrade the data.

Light scattering by a gas depends linearly on its density, so the temperature and pressure of the calibration gas in the scattering chamber are measured and the light-scattering coefficient of the gas under those conditions is calculated. These two data points define a straight line. The response of integrating nephelometers is typically linear, so the straight line is the calibration curve relating the instrument response to the light scattering in the sample chamber.

One of the calibration gases is particle-free air, which can be obtained by passing ambient air through a filter. This air contains the ambient concentrations of water and CO_2, which is desirable because they affect the light-scattering coefficient. In CRPAQS, the nephelometers will be calibrated to read zero when filled with particle-free air. Therefore, the particle-free air is sometimes called the "zero gas." The Radiance Research Nephelometers used in CRPAQS contain a temperature sensor. The signal processing electronics in the nephelometer calculates the light scattering by air at the measured temperature and subtracts the calculated value from the measured signal. Thus, the zero reading is automatically compensated for changes in ambient temperature. The ambient pressure is set by the user (See Section 9.1) according to the site elevation, and remains constant.

The scattering coefficient for air is reported by Bucholtz (1995). The scattering coefficient for the effective wavelength of the Radiance Research nephelometer is given in Table 1 of Section 6.3 of the Radiance Research manual (Radiance Research, 1999).

The other calibration gas should have a higher light-scattering coefficient and produce an upscale reading. This gas is sometimes called the "span gas." The two best choices are CO_2 and HFC 134a, also known by the duPont trade name, SUVA. CO_2 has the advantages that it is inexpensive, widely available, and its use causes negligible environmental effects, so generous flows of the calibration gas can be used to assure that the scattering chamber contains only the calibration gas. Calibrations can also be continued for many averaging times to evaluate instrument noise. The scattering coefficient of CO_2 is a factor of 2.61 times greater than for particle-free air. SUVA has the advantage that it has a higher light-scattering coefficient, which is 7.35 times greater than for particle-free air.

Scattering coefficients for some span gases for the effective wavelength of the Radiance Research nephelometer are reported in Table 1 of Section 6.3 of the Radiance Research manual.

The following section describes a rapid calibration procedure that can be executed quickly in the field. This procedure maximizes the number of sites a field operator can visit in one day. SUVA will be used for this calibration procedure during CRPAQS, but any span gas could be used. Section 10.3 describes a more lengthy calibration procedure that results in recording 5-min average zero and span data in the nephelometer memory.

Neither of these calibration procedures results in a change in the zero and span settings stored in the nephelometer. Those settings should be changed only when required by some instrument malfunction.

10.2 Rapid Field Calibration

If this calibration procedure is started early in one 5-min averaging period and ample calibration gas flows are used, it is possible to complete the procedure during one averaging period so that only one data point is lost from the ambient monitoring record. However, it is recommended that the stability of the zero and span readings be observed for a long enough time that the calibration continues into the second 5-min averaging period. If the nephelometer operation is restored about 2 min before the end of an averaging time, the following 5-min average will be a valid ambient reading.

No computer connection to the serial port is required for this calibration procedure. Normally, the nephelometer clock is adjusted to the correct time when a computer is connected to dump data (see Section 11.3). It is recommended that the nephelometer be left in the Log Mode during calibration. It is recommended that the mode not be changed to the fast mode because data are not recorded in the nephelometer memory in this mode.

11. Fill the nephelometer with particle-free air. Shortly after the beginning of a 5-min averaging time period, record the time displayed on the **Main Screen** when the calibration was started. Open the valve that allows air to enter the filter connected to the calibration gas fitting at the base of the nephelometer. Remove the heater, move the sample air fan from the lower port to the upper port, and plug the lower port with a flexible stopper or a piece of packing tape placed flat over the end of the port. (Plastic pipe fittings may not completely seal the port.) The sample air pump will draw filtered air into the scattering chamber. At least 3 or 4 minutes are required to obtain a stable reading. (A larger sample air pump could be used to decrease the time required to obtain a stable reading.)
12. Obtain and record a stable light-scattering reading. Observe the light scattering reading in the main screen as it decreases to near zero. The approach of the reading to the new value can be accelerated by momentarily toggling the **Reset** switch to the **Average** position. This clears the memory location used in the calculation of the nephelometer reading after the application of a time constant. When a stable reading is obtained, record a few light-scattering readings and the displayed time for each. Readings within ±0.20e-5 m^{-1} (±2 Mm^{-1}) of zero are normal. Readings greater than 1.0e-5 m^{-1} (10 Mm^{-1}) indicate spider webs or a dirty light trap. See the Manual Section 9.1 and Section 14 of this SOP for cleaning procedures. Toggle the **Display** switch in either direction until the temperature and RH is displayed, and record the temperature and RH readings. Return the display to the **Main Screen**.
13. Fill the nephelometer with span gas. Disconnect the sample air pump and plug the upper port with a stopper that contains a small hole or with packing tape that covers all but a small part of the top of the opening. The lower port should remain plugged. Attach the tube from the span gas container to the tube leading to the filter connected to the calibration gas fitting at the base of the nephelometer. Turn on the span gas flow. The span gas should flow through the filter, into the base of the nephelometer, and out the sample-air port at the top of the nephelometer.
14. Obtain and record a stable light-scattering reading. The procedure is the same as in step 2 above, except that the reading will become stable at an upscale value. The RH reading should be close to zero. Usually, the light-scattering reading will be stable and within about 5% of the expected value (see Step 7 below). When the **Reset** switch is toggled to **Average**, it is necessary to wait at least 30 sec for a valid reading.
15. Restore the nephelometer to the monitoring configuration. Shut off the span gas flow, unplug the supply tube, and close the valve near the filter so that no air can flow through the filter. Unplug the sample air inlet and replace the sample air fan.
16. Confirm nephelometer operation. Double check the plumbing connections to assure that the sample airflow is correct. Check that the time displayed in the **Main Screen** is advancing and the light scattering reading is returning to a reasonable value for ambient conditions. Record the displayed time that the collection of valid data resumed.
17. Review the calibration data. Review the record of the calibration to be sure it is complete and contains no errors. Calculate the expected span value from the data in Table 1 of

Section 6.3 of the Manual. For example, the expected span value for CO_2 is 2.30e-5 (273 K/nephelometer temperature reading)(barometric pressure/1013 mb) m^{-1}

The temperature should be obtained from the nephelometer screen and the pressure from a barometer (not the pressure manually set in the nephelometer). All readings by the nephelometer, including this span value, indicate the amount by which the light scattering is greater than the scattering by particle-free air.

The following two paragraphs give the recommendations at the start of the CRPAQS field measurements: If the measured zero differs from zero by more than 0.50e-5 m^{-1} (5 Mm^{-1}) or the span value differs from the expected value by more than 10% at an Anchor Site, report the result to Beth Witting and to will@sonomatech.com. Do not change the nephelometer zero unless it differs from zero by more than 1.0e-5 m^{-1} (10 Mm^{-1}) in two independent calibrations. If the change in zero is very large or occurred suddenly, it was probably caused by dust or spider webs in the scattering chamber. Cleaning the nephelometer may be better than adjusting the zero.

Do not change the nephelometer span calibration unless it differs from the expected slope by more than 20% in two independent calibrations when the ambient temperature is below 30°C (86°F). The slope is the difference between the zero reading and the span reading. It is possible that slopes as much as 20% below the expected value will be observed at high ambient temperatures. Such observations should be recorded but should not trigger a recalibration of the nephelometer.

The analysis of the calibration and audit data from the CRPAQS Satellite sites described in Section 9.3 show that the nephelometer zeros should generally be stable to within about 2 Mm^{-1} and the slopes to about 5% of the expected value. Therefore tighter constraints could have been used. For example, it is reasonable to change the nephelometer settings if the zero changes by more than 5 Mm^{-1} or the span changes by more than 10%.

The above calibration procedure causes invalid data to be recorded while the calibration is in progress. The purpose of recording the time the calibration is started and ended from the display on the **Main Screen** is to identify these data for later flagging as invalid due to calibration. Useful calibration data are stored in the nephelometer memory only if a stable reading is maintained throughout a 5-min averaging period.

10.3 Extended Calibration

It is possible to extend the time period of the calibration so that 5-min average calibration data are recorded in the nephelometer memory and become part of the archive data record. This is accomplished by obtaining stable calibration readings before the start of a 5-min averaging period and maintaining stable conditions through end of that period. This procedure requires 5 min each to record the zero and span values and three 5-min averaging periods to stabilize the nephelometer at the two span values and then for ambient monitoring. Thus, 25 min of ambient monitoring are lost.

This calibration procedure differs from the one described in Section 10.2 only by maintaining stable calibration conditions during a complete 5-min averaging time.

- The calibration procedure is started using steps 1 and 2 in Section 10.2, except that the light scattering, temperature, and RH readings can be recorded midway through the 5-min averaging period during which the zero value is stable.
- The span calibration is performed using Steps 3 and 4 in Section 10.2, except that the light scattering, temperature, and RH readings can be recorded midway through the 5-min averaging period during which the span value is stable.
- The calibration is completed using Steps 5 through 7 in Section 10.2.

The same form as in Section 10.2 may be used to keep a record of the extended calibration and its results. The tolerance limits beyond which corrective actions are required are the same as describe in Section 10.2.

11. INSTRUMENT OPERATION

11.1 Quick-Start Instructions

The Radiance Research M903 Nephelometer is self-calibrating, so it is only necessary to plug it in and turn it on to begin collecting valid data. The following steps are adequate to begin data collection:

1. Assemble the sample airflow system. At a minimum, this includes inserting the sample air fan in the sample air outlet, which is the lower gas flow port on the body of the nephelometer. It is highly desirable to have the sample-air heater and bug screen on the inlet.
2. Turn the red power switch on the nephelometer off. Plug the sample air fan power cord into its connector near the base of the nephelometer. Plug the 12 V power supply into the connector near the base of the nephelometer and a source of 115 V AC power. Connect the sample air heater controller RH input signal to the RH signal output at the base of the nephelometer. Turn on the red power switch on the nephelometer.
3. Be sure the operating mode, averaging time, time of day, and date shown in the **Main Screen** are correct. In CRPAQS, the nephelometers will be operated in the Log mode with a 5-min averaging time. As an optional confirmation, the data on the display screens described in Section 9.1 could be reviewed.

11.2 Checklist for Initial Operation

This checklist assumes that the nephelometer has passed the acceptance test described in Section 9.2, been installed in an environmental shelter as described in Section 8.3, and that the sample air heater with a bug screen and controller have been installed as described in Section 8.2.

The following checklist confirms only the setup of the nephelometer itself. In most cases, it is expected that the only nephelometer settings in need of change will be the time and the ambient pressure appropriate for the site elevation. The nephelometer display screens are described in Section 9.1.

1. On the **Main Screen**, check the date, time, and operating mode. The mode should be "Log 5 min." If necessary, use the **Mode Change Screen** to change to the log mode. If the averaging time is different from 5 min, change it as described in Step 6.5 below. Step 6.4 describes setting the clock in the nephelometer.
2. On the **Zero Calibration Screen**, confirm that the 5-digit number in the lower right of the screen equals the factory calibration listed in the back of the Radiance Research manual or the value determined during the acceptance test. See Section 9.1 if this number needs to be changed.
3. On the **Span Calibration Screen**, confirm that the 5-digit number in the lower right of the screen equals the factory calibration listed in the back of the Radiance Research manual or the value determined during the acceptance test. See Section 9.1 if this number needs to be changed.
4. On the **Photomultiplier Adjust and Diagnostic Screen**, check that the greater than sign moves back and forth between the "scat" and "span" readings, and that the reading marked by this sign is frequently updated. Confirm that the 4-digit number in the upper right of the screen equals the photomultiplier voltage listed in the back of the Radiance Research manual. See Section 9.1 if this number needs to be changed.
5. Use the **Set Local Pressure Screen** to set the pressure to a value corresponding to the site elevation. This can be calculated from the formula

   $$\text{Pressure} = 1013\ ((288 - 0.0065 \text{ site elevation in m})/288)^{5.256} \text{ mb.}$$

   A spreadsheet with the pressures calculated for each CRPAQS site is available from T&B Systems.
6. Use the **Serial Port Adjust Screen** to set a baud rate compatible with the computer used to communicate with the nephelometer. A baud rate of 9600 is recommended, if possible.
7. Return the display to the **Main Screen**.
8. Connect a computer to the serial port as described in Section 8.5.
   - 8.1. Verify that data are sent to the computer every flash (approximately twice per second).
   - 8.2. Enter "s" to stop data transfer and display a command menu. (Either upper or lower case can be used for all commands.)
   - 8.3. Enter "m <Enter>" to mark the data in the nephelometer memory, so the next has the option of dumping data recorded only after this setup.

8.4. If the time viewed in Step 1 above was incorrect, enter "t hhmm <Enter>" to enter the correct time as prompted on the computer screen. The seconds are set to zero when the time is entered.

8.5. Enter "z <Enter>" to view the setup of the log mode. The displayed parameters should match those in Table 9-1. If the averaging time viewed in Step 1 above was different from 5 min, enter "h <Enter>" and adjust the averaging time parameter to 133. The commands to change the other parameters appear on the menu on the computer screen.

8.6. Press <Enter> to return to the main menu and then "q <Enter>" to resume data acquisition. The time on the **Main Screen** should begin advancing and the data should be sent to the computer every flash. If not, repeat the "q <Enter>" command.

8.7. Disconnect the computer from the serial port.

9. View the **Main Screen** to again check that the clock is advancing, the time and date are correct, and the mode is correct (see Step 1).

11.3 Transferring Data to a Computer

It is recommended that the archive data from all Radiance Research Nephelometers be derived from the short-format data dumps from the nephelometer memory. The analog data recorded by the data loggers at the Anchor Sites should be replaced by the digital data in the archive record. The procedure for dumping the digital data is described in Section 8.5 above. At the completion of the data dump, the operator should remember to resume data acquisition and should double check the time in the **Main Screen** to be sure that the displayed time is advancing. Monitoring data will not be recorded in the nephelometer memory if the operator neglects to resume data acquisition after performing a data dump.

11.4 Checklist for Site Visits

Figure 11-1 shows a form that can be used by the field technicians to record observations during a visit to a Satellite Site. Additional comments can be written on the back of the form. As indicated by the note in italics added to the bottom of this form, it was an error not to include spaces to record the five-digit integer values for SET ZERO and SET SPAN on this form. These integers indicate the zero and span settings stored in the nephelometer. These were sometimes changed without adequate documentation. If these values had been recorded each site visit, the uncertainty in the time when unrecorded changes in the calibrations occurred would have been smaller.

REPORT OF A VISIT TO A SATELLITE SITE
FOR THE RADIANCE RESEARCH M903 NEPHELOMETER

Operator name ______________________ Site name _______________ Date___________

Nephelometer time ______________ Correct time ________________

The nephelometer time is ______ minutes and ______ seconds fast / slow.

DATA DUMP

Nephelometer clock time when nephelometer data recording was stopped ________________

Were the data marked after the dump? yes / no

Was the nephelometer clock reset? yes / no (Reset clock if more than 30 sec error.)

Nephelometer clock time when the nephelometer data recording was resumed ___________

The nephelometer time is now ______ minutes and ______ seconds fast / slow.

GAS CALIBRATION *Do not change the stored calibration settings without an OK.*

Nephelometer clock time when nephelometer data recording was stopped ________________

Light scattering readings for filtered air ______|______|______|______|______|______|m^{-1}
Time of readings ______|______|______|______|______|______|

Nephelometer internal temperature _________ K RH _____________ percent.

5-min average zero recorded? yes / no Start time __________ End time _________

Light scattering reading for span gas ______|______|______|______|______|______|m^{-1}
Time of readings ______|______|______|______|______|______|

Nephelometer internal temperature _________ K RH _____________ percent.

5-min average span recorded? yes / no Start time __________ End time _________

Nephelometer clock time when the nephelometer data recording was resumed ____________

FINAL CHECK

Before closing the shelter: Was the nephelometer clock advancing? yes / no

Nephelometer time ________________ Light scattering reading ____________ m^{-1}

COMMENTS

Record comments on the status of the nephelometer system and on local observations that may affect the nephelometer data. Additional comments on the back of this form? yes / no

Figure 11-1. Form to record data from a site visit. The form should have included places to record the 5-digit integer SET ZERO and SET SPAN values each visit. These values were sometimes changed during CRPAQS without an adequate record of the change.

At the end of each site visit, the operator should double check that the nephelometer clock is advancing. It is necessary to stop data acquisition to dump the data from the nephelometer memory. All monitoring data are lost until the data acquisition is resumed. The clock display in the **Main Screen** stops when the data acquisition is stopped, but begins advancing again when data acquisition is resumed.

12. HANDLING AND PRESERVATION OF SAMPLES

This section is not applicable. No samples are collected by a nephelometer.

13. SAMPLE PREPARATION

This section is not applicable. No samples are collected by a nephelometer.

14. PREVENTIVE MAINTENANCE AND REPAIRS

The only preventive maintenance required for the integrating nephelometer is to periodically remove the bug screen from the inlet of the sample air heater and clean it. Normally, brushing or blowing off the accumulated dust is adequate. It may be necessary to wash the screen. This screen should be inspected each time the nephelometer is visited.

The power plug on some nephelometers is not as tight as would be ideal. The operator should be sure this plug is inserted all the way on each visit.

When the zero calibration indicates that the nephelometer has a spider web in the scattering volume, the nephelometer should be opened and cleaned as described in Section 9 of the Radiance Research nephelometer manual. Spider webs typically cause zero readings greater than 100 Mm^{-1}, can cause readings greater than 1000 Mm^{-1}, and the readings are often variable.

The accumulation of dust on the light trap and other parts of the nephelometer will cause the zero readings to increase with time. When the zero reading exceeds 10 Mm^{-1} for two successive zero calibrations, the nephelometer should be opened and the dark trap cleaned as described in Section 9 of the Radiance Research nephelometer manual.

The screen on the air inlet of the shelter should also be inspected each time the nephelometer is visited and cleaned when necessary. The black standpipe in the back of the shelter can be removed and screen can be brushed while air is blown backwards through the screen. It may be necessary to pour water through the screen if deposits build up on the screen during fog events.

The fit of the shelter door should also be inspected from time to time. If the door is held closed by a tapered peg through the eyebolt, inserting the peg more firmly can tighten the door.

When a lock is used on the eyebolt, the eyebolt can be turned to adjust how tightly the door is held closed when the lock is in place.

In summary, the screens on the air inlet to the shelter and nephelometer should be inspected each visit and cleaned when necessary. The power plug in the nephelometer should be checked to be sure it is fully inserted. The nephelometer should be opened and cleaned when indicated by the zero calibration.

15. TROUBLESHOOTING

The great majority of problems with nephelometer data during the first two months of CRPAQS field measurements have been due to operator error. Therefore, the first corrective action to take is to carefully review the instrument configuration and signal wiring to be sure that they are correct. If the problems occur during calibration, review the calibration procedures to be sure that they are being followed. Be sure that the power plug is fully inserted in the nephelometer.

Spider webs required some troubleshooting before adequate bug screens were installed. During the first two months of monitoring, there were no cases where the dark traps required cleaning. The methods for cleaning the nephelometer are described in Section 14 and in Section 9 of the Radiance Research manual.

16. DATA ACQUISITION, CALCULATIONS, AND DATA REDUCTION

The short format data dumps from the Radiance Research M903 Nephelometer yield ASCII data files in calibrated engineering units and can be imported directly into the archive data record. It is necessary to concatenate the dumped files to produce a continuous data record. If the field operators mark the data after each data dump and dump only unmarked data, no editing will be required to produce continuous data records. The continuity of the database should be checked when the data are concatenated.

The records from the site visits should be used to flag data recorded when calibrations or other instrument servicing was performed. If 5-min average zero or span data are recorded, they should be flagged appropriately. Data recorded during times when the data are known to be corrupted or invalid should be flagged or replaced by a missing data code.

The records from the periodic gas calibrations should be reviewed to see if correction factors should be applied to the dumped light scattering data. Based on the preliminary evaluation of the nephelometer performance, it is expected that the nephelometer span will show a large enough temperature dependence to justify applying a correction.

It is recommended that the light scattering readings from the Radiance Research nephelometer be labeled b_{sp} (or bsp when subscripts are inconvenient). This label makes in clear that the instrument is calibrated to read zero for particle-free air and that the readings are a measure of light scattering by particles. It is also recommended that the readings be multiplied by a factor of 1,000,000 in the final database so they are in units of inverse megameters (Mm^{-1}) instead of the inverse meters (m^{-1}) output by the nephelometer.

The calibration signal should also be multiplied by a factor of 1,000,000 to convert it to units of inverse megameters. Temperature and pressure are output in units of Kelvin (K) and millibars (mb) respectively, and can appear in the final database in those units.

When the calibration data are available, corrections may be applied to the b_{sp} data based on a review of extended periods of calibration data.

17. COMPUTER HARDWARE AND SOFTWARE USED

At the Anchor Sites, both the analog and digital nephelometer outputs are connected to the data logger. The analog data are continuously polled and recorded. The digital data are automatically dumped each night.

At the Satellite Sites, laptop computers are used to dump data from the nephelometer as described in Section 11.3. The dumped data in the nephelometer memory are marked to provide the option of not including them in the next data dump.

18. DATA MANAGEMENT AND RECORDS MANAGEMENT

There are no special requirements for the management of the data and records from the nephelometer. The standard CRPAQS data and records management procedures should be followed. It is expected that these procedures will archive the site visit forms, the separate data files dumped from the nephelometers, the concatenated data before calibration factors are applied, and the final data.

As with all measurements, it is expected that calibrations will be applied to the data once the calibration data become available for an extended time period.

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Instrument:	Radiance Research M908 Nephelometer
Worksheet:	Task 2 - Zero and span check with CO_2 (weekly) Task 3 - Zero and span check with SUVA (monthly in place of Task 2)
Site Code:	

Date	/ /	/ /	/ /
Field Tech			
Instrument SN			
Box SN			
Heater SN			
INITIAL CHECKS:			
DAS clock	: :	: :	: :
Neph clock	: :	: :	: :
Bs (e^{-5} m^{-1})			
GAS CALIBRATION:			
Zero-air			
Start time	: :	: :	: :
1st Bs (e^{-5} m^{-1}) / time	/	/	/
2nd Bs (e^{-5} m^{-1}) / time	/	/	/
3rd Bs (e^{-5} m^{-1}) / time	/	/	/
4th Bs (e^{-5} m^{-1}) / time	/	/	/
5th Bs (e^{-5} m^{-1}) / time	/	/	/
6th Bs (e^{-5} m^{-1}) / time	/	/	/
7th Bs (e^{-5} m^{-1}) / time	/	/	/
Internal T (K)			
Internal RH (%)			
Stop time	: :	: :	: :
Span gas			
Gas type?	CO_2 / SUVA	CO_2 / SUVA	CO_2 / SUVA
Start time	: :	: :	: :
1st Bs (e^{-5} m^{-1}) / time	/	/	/
2nd Bs (e^{-5} m^{-1}) / time	/	/	/
3rd Bs (e^{-5} m^{-1}) / time	/	/	/
4th Bs (e^{-5} m^{-1}) / time	/	/	/
5th Bs (e^{-5} m^{-1}) / time	/	/	/
6th Bs (e^{-5} m^{-1}) / time	/	/	/
7th Bs (e^{-5} m^{-1}) / time	/	/	/
Internal T (K)			
Internal RH (%)			
Stop time	: :	: :	: :
FINAL CHECKS:			
Neph clock advancing?	Yes / No	Yes / No	Yes / No
Bs (e^{-5} m^{-1}) and time			
RECORDKEEPING:			
File name			
Copied to disk?	Yes / No	Yes / No	Yes / No
Zero-air			
5-min averages recorded?	Yes / No	Yes / No	Yes / No
Average bs (e^{-5} m^{-1})			

Span gas			
External P (mb)			
5-min averages recorded?	Yes / No	Yes / No	Yes / No
Average bs (e^{-5} m^{-1})			
Expected bs (e^{-5} m^{-1})			
% Difference			

Formula:

T (K) = T (C) + 273.15

P (mb) = P (in Hg) x 33.86 = P (mm Hg) x 1.33

Expected CO_2 bs (m^{-1}) = $2.30e^{-5}$ x 273 K x P (mb) / Internal T (K) / 1013 mb = $6.2e^{-6}$ x P (mb) / Internal T (K)

Expected SUVA bs (m^{-1}) = $9.06e^{-5}$ x 273 K x P (mb) / Internal T (K) / 1013 mb = $2.44e^{-5}$ x P (mb) / Internal T (K)